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Short time-scale impacts of hydropeaking on benthic invertebrates in an Alpine stream (Trentino, Italy)

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ABSTRACT

The impact of a single hydropeaking event was studied in the Alpine stream Noce Bianco. Four stations were selected, one upstream and three, respectively, at 0.25, 6, and 8 km downstream from a hydropower plant. We collected drifting invertebrates during a planned water release that increased the discharge 7-fold. At the onset of the hydropeaking wave the number of invertebrates lost from the riverbed per minute to the drift increased 9-fold at the first downstream station and the same effects propagated 8 km downstream. The drift was composed mainly of aquatic insect larvae (Chironomidae, Plecoptera, Ephemeroptera Baetidae, and Psychodidae, with Chironomidae as the most abundant taxon at all stations) and partly by larval and adult riparian insects, and by Oligochaeta, which were particularly abundant at the station 6 km downstream. We monitored drift for 30 min from the start of the water release: peaks in drifting invertebrates occurred within 5–10 min of the beginning of the hydropeaking wave, and most of the invertebrates were washed out within the first 15 min of the water release. The different timeframes were possibly due to habitat preferences (most of the taxa that increased in the drift at the arrival of the wave were associated with algae and organic debris, which were washed off quickly by the increase in discharge) and/or behavioral adaptations (other taxa initially resisted the shear stress and began to drift with a delay of 5–10 min). The temporal pattern and drift composition corresponded well with those reported in literature, and indicate that repeated high-flow events of similar magnitude cause considerable losses from benthic populations to drift.

Introduction

In Alpine regions, intermittent hydropower generation has high economic importance. Although it is the most relevant renewable electricity source with clear advantages for the global CO_2 balance (Bratrich et al., 2004), it creates serious ecological impacts on aquatic ecosystems (e.g. Poff and Hart, 2002; Fette et al., 2007). Changes in flow regime associated with hydropeaking are known to decrease both the density and biomass of benthic invertebrates downstream from hydropower plant outlets (Irvine, 1985; Céréghino and Lavandier 1998a, b; Céréghino et al., 2002, 2004) by increasing the intensity of bed scour (Brittain and Eikeland, 1988), which in turn leads to a high catastrophic drift (Gore et al., 1989), and by clogging of the riverbed because of deposition of the fine material transported by released water (Blaschke et al., 2003; Anselmetti et al., 2007), which reduces the available habitat for the bottom-dwelling fauna. As a consequence, the specific composition and longitudinal zonation of invertebrate populations below the outlet are altered (Céréghino and Lavandier 1998a, b).

Drift is an important process in regulating population densities, dispersal, and life cycles of benthic invertebrates in rivers and streams (Brittain and Eikeland, 1988; Céréghino and Lavandier 1998a, b; Mochizuki et al., 2006). Most of the studies on drift have been conducted at normal or base flows (e.g. Brittain and Eikeland, 1988; Anholt, 1995), whereas catastrophic drift (*sensu* Culp et al., 1985, i.e. generated by any disturbance) caused by natural or artificial floods have been less well investigated (Statzner et al., 1988; Gibbins et al., 2007a, b). Because the time and magnitude of floods or flashes are hard to predict in natural streams and rivers, and sampling in such conditions is often very difficult, studies on precise temporal sequences of drift during such events are few (Tockner and Waringer, 1997). As a consequence, drifting organisms are not easy to collect during natural floods, other than during some artificial floods (Robinson et al., 2004a) or in experimental channels (Gibbins et al., 2005; Mochizuki et al., 2006). Drift is usually associated with flood conditions, during which the substrate is physically disturbed. Despite the clear role that sediment mobilization plays in initiating drift, considerable drift can also occur in the absence of sediment movement; the effects of non-scouring increases in

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flow are not less dramatic for benthic communities than those of catastrophic floods (Imbert and Perry, 2000; Gibbins et al., 2007a, b), and drift can also occur when sediment is being agitated rather than being transported downstream and extremely high drift losses can occur in conditions that hydrologists and geomorphologists would not consider to be disturbance (Gibbins et al., 2007a, b).

Gibbins et al. (2000) demonstrated the impacts of discharge increase due to inter-basin water transfer on the insect *Micronecta poweri*, on a short-term water transfer (1 h) that increased the discharge 3-fold, where the sediment was not mobilized, and only FPOM was removed; as a consequence the average total abundance of *M. poweri* was reduced by approximately 50% during the transfer. To our knowledge, however, the effects of non-scouring flood induced by hydropeaking on the entire benthic assemblages have not been investigated. Moreover, the effects of hydropeaking on benthic communities have been extensively investigated on a large time-scale, i.e. the effects of multiple natural or artificial floods or hydropeaking events (e.g. Céréghino and Lavandier, 1998a, b; Céréghino et al., 2002, 2004; Hay et al., 2008). On the other hand, our study investigates non-scouring drift due to water released from a dam and turbinated in a hydropower plant on a short time-scale.

This study assessed the aquatic invertebrates response to a hydropeaking wave, aiming to answer the following questions:

1. What are the effects on invertebrates of the arrival of the hydropeaking wave, and how far downstream do such effects propagate?
2. Can a temporal timeframe be detected in drift for different taxa, even if the discharge, once artificially increased, remains constant?

Materials and methods

Study area

The spatial (downstream from the disturbance) and temporal (from the onset of the hydropeaking wave) effects of a planned hydropeaking release on benthic and hyporheic communities were studied in the Adige watershed (NE Italy, Trentino). The Adige River is the second-longest Italian river, draining a 12,100 km^2 basin and, like most large Alpine rivers, it has been greatly altered by hydropower production. To date, there are 30 major reservoirs in the watershed with a total capacity of 571×10^6 m^3, supplying 34 hydropower plants. Field experiments were conducted on the Noce Bianco Stream (Trentino, NE Italy, 46°24′N, 10°40′E), a 3rd order stream and left tributary of the Noce Stream (Fig. 1), which in turn is a main tributary of the Adige River. The Noce Bianco (watershed = 35.9 km^2) is a gravel stream with 4–20 m wetted width. It is a glacial (kryal) dominated stream, fed by the Vedretta de la Mare and Careser glaciers, whose snouts are at about 2800 m a.s.l., with some minor non-glacial (krenal and rhithral) tributaries. The sampling stations were located downstream from the Cogolo hydroelectric power plant, which uses waters from the Careser (2603 m a.s.l.) and Pian Palù (1850 m a.s.l.) reservoirs. From the Careser dam, water falls for 622 m until it reaches the Malga Mare plant (1963 m a.s.l.), where it is turbinated and discharged to a sedimentation basin that also collects water from the Noce Bianco Stream. These waters together with water from Pian Palù reservoir are delivered to the Cogolo plant (1208 m a.s.l.), where they are discharged into the Noce Bianco Stream. Three sampling stations were selected, located, respectively, 0.25, 6, and 8 km downstream of the release point: B (1197 m a.s.l.), C (1054 m a.s.l.), and D (988 m a.s.l.; Fig. 1).

On September 24th, 2006, a planned release corresponding to the normal operational conditions (no release during the night, followed by a release at maximum turbine capacity) was arranged with the managing agency (ENEL). The power plant started to turbinate at 12:55; the hydropeaking wave traveled downstream at about 5 km h^{-1} and reached stations B–D after 25, 85, and 101 min, respectively. Discharge increased from 1 to 7 m^3 s^{-1} within approximately 10 min.

Physical–chemical and hydraulic parameters

Water temperature and conductivity were recorded at 1-min intervals before and during the hydropeaking event at each station with a Hanna® HI 8730 portable conductivity and temperature meter. Conductivity was automatically corrected to the standard temperature of 20 °C. Water level was measured 15′ before the hydropeaking event at all stations, and 10′ after its arrival at stations B–D by averaging three measurements (left side, mid-channel, right side). Water velocity was measured with a current meter before and during the hydropeaking wave, at stations B–D; the current meter was placed as close as possible to the drift net; it was not possible to place it directly in front of the nets because these were lowered from a bridge.

Water samples were collected at each station before the hydropeaking event and every 2 min during the event, refrigerated, and carried to the laboratory, where turbidity measurements were taken with a Hanna® HI 93703 Portable Turbidity Meter.

The bedload material movement during the hydropeaking events was estimated by spraying with red paint 10 pebbles and boulders of increasing size and placing them on the bottom at each station, and observing if they had moved and/or relocated at the end of the experiment. In addition, a visual estimation of bedload movement was conducted. Granulometry (D_{90}) was measured with a gravelometer at stations B and C.

Biological sampling

At stations B–D, quantitative drift samples were collected using three drift nets (mesh size 100 μm, mouth diameter 10 cm, length 1 m) placed side by side on a horizontal metal bar that was lowered into the stream below the water surface from bridges. Each one of the three nets represented one replicate; thus we had three replicates per sample. Four consecutive samples obtained by collecting the drifting invertebrates for 15 min were taken before the water release at each of the three stations (samples 1–4, called "before" drift samples herein). Six consecutive samples, each obtained by collecting the drifting invertebrates for 5 min, were taken during the water release at each station (samples 5–10, called "during" drift samples herein). Thus, the last sample was taken at each station 30 min after the onset of the hydropeaking wave. Different collecting times were necessary in order to follow the changes in drift over a short time period during the release. Little or no clogging of drift nets occurred as suspended sediment is low in autumn in Alpine streams. Filtered volumes were calculated according to water velocity as measured at each station during the experiment.

All samples were sorted in the laboratory and organisms identified to the lowest possible taxonomical level following Campaioli et al. (1994, 1999) and Fochetti et al. (2009). Many Insecta early instars could not be identified further than the order or family level. All Copepoda were sorted and counted under magnification, mounted on permanent slides, and examined with

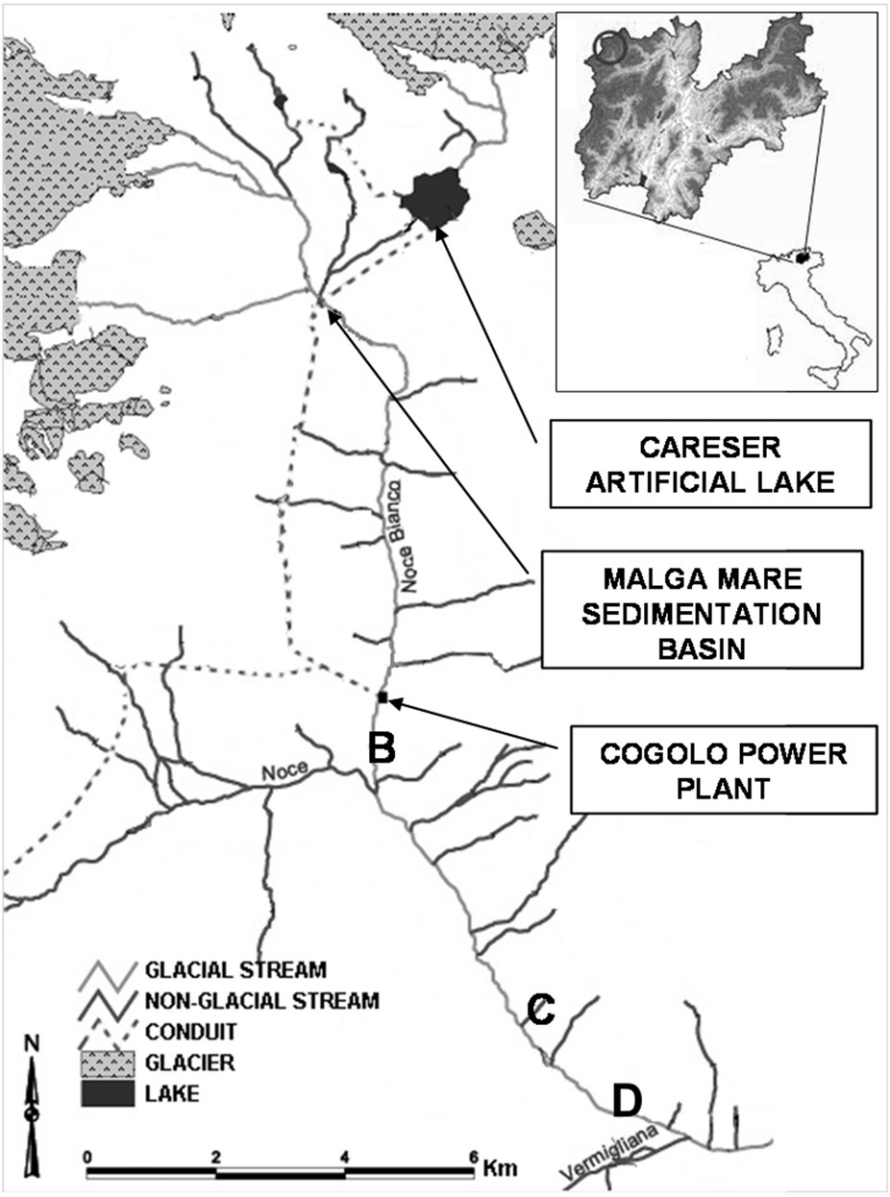

Fig. 1. Study area and sampling stations in the Noce Bianco Stream, Trentino, Italy. Stations B–D were located, respectively, 0.25, 6, and 8 km downstream from the Cogolo hydropower plant.

phase contrast microscopy and adults and copepodites at stage V were identified to the species level following Dussart (1967, 1969), Stoch (1998), Karaytug (1999), and Pesce and Galassi (1987). Individuals of earlier larval stages (i.e. copepodites) were not identified, but were labelled "copepodites", and when possible identified to the genus level. Because unidentified early larval stages of copepods could not be classified, they were used only when calculating the total abundances of benthic invertebrates, but not for other statistical analysis (see details below).

Statistical analyses

The terrestrial taxa (Araneae, Miriapoda, adults of Diptera, Hemiptera, Ephemeroptera, Thysanoptera, and riparian Coleoptera; Formicoidea, Hymenoptera, terrestrial Isopoda, larvae of Lepidoptera, Collembola), and the planktonic ones (the Copepoda *Acanthodiaptomus denticornis* and *Cyclops abissorum tatricus*, and Cladocera) were removed from the statistical analysis, because they do not belong to the benthic communities; the planktonic taxa were probably introduced with the water coming from the reservoirs, and the terrestrial taxa, which were rare (5% of the total), were probably washed out from the riparian area. For drift samples, first we calculated drift rate (numbers per minute) for all taxa; then we divided that rate by the volume of water that passed through the net during the sampling period; this gave us the density of drift per minute (individual m^{-3} min^{-1}).

A faunistic matrix was thus created, including a total of 90 drift samples (three replicates of ten samples collected at each station). The species assemblages were analyzed by applying a non-metric multidimensional scaling (NMDS) to a resemblance matrix calculated with the Bray–Curtis similarity index applied to the dataset. Prior to analysis, abundance data were transformed to proportions, so that the NMDS depicted patterns in species composition and relative abundance.

We performed analyses of similarity on drift samples (ANOSIM) (Clarke, 1993) on the faunistic matrix transformed in $\log(x+1)$, in order to analyze possible changes in drifting

assemblages over time and distance from the disturbance. In particular, we tested for: (i) differences over time and before–during the hydropeaking wave at each station, in the latter case, with the samples divided into two groups; all samples collected before the beginning of the wave (samples 1–4) and those collected during the wave (samples 5–10). We ran one analysis for each of the three stations for each of the two factors (one-way ANOSIM, factor: TIME; factor: BEFORE–DURING); (ii) differences among stations over time samples, and among time samples over stations (two-way crossed ANOSIM with replicates, factor: STATION × TIME); (iii) differences among stations over before–during samples (two-way crossed ANOSIM with replicates, factor: STATION × BEFORE–DURING). The *R* significance values of pairwise comparisons between time samples obtained with the two-way crossed ANOSIM STATION × TIME were used to build a resemblance matrix that was the input for a NMDS analysis.

A Similarity Percentage (SIMPER) analysis (Clarke, 1993) was performed to detect how much two groups of samples differed, and which taxa contributed to the dissimilarity: (i) between couples of stations (factor: STATION) and (ii) before and during the hydropeaking wave at all stations (factor: BEFORE–DURING). SIMPER calculates the mean Bray–Curtis Dissimilarity Index between two groups and contributions of each taxon to the average dissimilarity between groups.

All analyses were performed using Primer 6 version 6.1.6 (Clarke and Gorley, 2006), and Statistica version 8.1 (StatSoft Inc., 2008).

Results

What are the effects on invertebrates of the arrival of the hydropeaking wave, and how far downstream do such effects propagate?

A total of 12,086 individuals, ascribed to 35 identified aquatic invertebrate taxa, were collected in the drift samples. The most abundant taxa (comprising 95% of the total) were, in decreasing order of total abundance, larvae and pupae of Chironomidae, Oligochaeta, larvae of Plecoptera and Baetidae, larvae and pupae of Psychodidae, and larvae and pupae of Trichoptera. Chironomidae were the most abundant taxon at all stations (Table 1). Most insect larvae were represented by early instars, especially for Plecoptera, Baetidae, and Trichoptera (EPT) taxa, which could not be identified at a high taxonomic level. Overall, EPT tended to decrease in abundance with distance from the release point, Chironomidae and Psychodidae increased, and Oligochaeta peaked in abundance at station C (Tables 1 and 2).

The impact of the hydropeaking wave on abundance and composition of drifting invertebrates propagated 8 km downstream with a spatial (i.e. longitudinal) effect. The total number of benthic invertebrates lost to drift was 92 m^{-3} s^{-1} at B (26 taxa), 153 ind m^{-3} s^{-1} at C (33 taxa), and 91 ind m^{-3} s^{-1} at D (20 taxa; Fig. 2). The composition of the drifting invertebrate assemblages changed significantly with distance from the turbinated water release at each station (two-way crossed ANOSIM, test for differences between station groups across all time samples, R=0.683, p=0.001) and drift samples collected at each station formed distinct groups across the NMDS ordination (Fig. 3); drift composition at C was the most different from those of the two remaining stations, which were more similar and thus grouped closer on the NMDS plot (Fig. 3); the mean dissimilarity indices scored in the SIMPER analysis 62.58 for B and C, 60.26 for C and D, and 53.51 for B and D. Differences between stations (Table 2) were mainly due to high abundance at B of Plecoptera (representing there 10.6% of the total, 5.1% at C, and 2.3% at D) and Baetidae (7.0% of the total at B, 3.5% at B, and 4.0% at D). Higher abundances of Oligochaeta (1.1% of the total at B, 30.7% at C, and 1.5% at D) and Psychodidae (1.3% of the total at B, 4.2% at C, and 3.0% at D) characterized C, and Chironomidae characterized D (60.5% of the total at B, 50.95% at C, and 71.8% at D). The distribution of some rare taxa differed as well; for instance Copepoda Harpacticoida represented 1.9% of the total and 9 identified taxa at B, 0.1% and 6 identified taxa at C, and were absent at D.

The immediate response of the benthic invertebrates to the arrival of the hydropeaking wave was a strong increase in drift, with different intensities among taxa and among stations. The composition of drifting invertebrate assemblages differed significantly before and during the hydropeaking wave across stations (two-way crossed ANOSIM, testing for differences between "before" and "during" samples across all stations; R=0.799; p=0.001) and at each station (one-way ANOSIM, factor BEFORE–DURING, Table 3). Drift at B increased 8.7-fold during the wave, from a mean of 0.6 ind m^{-3} min^{-1} before the hydropeaking wave to 4.8 ind m^{-3} min^{-1} during the wave, when it was largely due to Chironomidae, Plecoptera, Baetidae, and Trichoptera; the number of identified taxa found in the drift increased at this station from 18 to 24 during the hydropeaking wave (Table 1). Similarly, at D, drift increased 9.1-fold, from 0.5 to 4.7 ind m^{-3} min^{-1}; the number of drifting taxa increased from 10 to 19, the increased abundance was mostly due to Chironomidae and Baetidae (Table 1). At C, on the other hand, the drift increased less, i.e. 4.2-fold, from 1.8 to 7.3 ind m^{-3} min^{-1}; while the number of drifting taxa decreased (from 27 to 20), due to the absence in the "during" samples of several taxa of Harpacticoida and Cyclopoida, which were rare but present in the "before" samples. Drift was mainly due to Chironomidae, Oligochaeta, Plecoptera, Psychodidae, and Baetidae (Table 1). Drift samples collected before and during the hydropeaking wave formed distinct groups across the NMDS ordination for each station, the most distinct group being the "before" and "after" samples collected at station C (Fig. 3). The NMDS of the pairwise comparison of R values of the ANOSIM analysis of time samples across all stations, which displays the relationship between the composition of drift over time, clearly separates the time samples collected "before" the hydropeaking wave from those collected "during" the wave (Fig. 4).

Drift samples were more similar in species composition during the hydropeaking wave than before it, grouping closer in the NMDS plot (Figs. 3 and 4); the SIMPER analysis resulted in an average dissimilarity index of 40.87 for samples collected during the wave and 45.81 for the pre-wave samples. The contribution to the dissimilarity between the two groups was due mainly to Oligochaeta (43.15% contribution to dissimilarity), Chironomidae (15.56% contribution to dissimilarity), Plecoptera (11.11% contribution to dissimilarity), Baetidae (8.00% contribution to dissimilarity), Psychodidae (6.14% contribution to dissimilarity), and Trichoptera (4.01% contribution to dissimilarity). All these taxa were more all abundant in the "during" samples (Fig. 5). Other taxa that were not dominant in the analysis but well represented, such as all the other Diptera larvae, were drifting more in the "during" samples as well (Fig. 5j). Terrestrial taxa, though not included in the statistical analysis, increased in drift with the hydropeaking wave 32-, 19-, and 6-fold, respectively, at B–D (Table 1, Fig. 5i).

Can a temporal timeframe be detected in drift for different taxa, even if the discharge, once artificially increased, remains constant?

The hydropeaking wave had an overall temporal effect. In fact, the composition of drifting invertebrate assemblages changed significantly over time across stations (two-way crossed ANOSIM, testing for differences between time samples across all stations, R=0.651; p=0.001) and at each station (one-way ANOSIM, factor TIME, Table 3). At all stations, peaks in drift abundance were

Table 1
Drift density of each taxon of aquatic invertebrates (ind m^{-3} min^{-1}) collected in each station in the Noce Bianco Stream (Trentino, Italy; for sampling stations, see Fig. 1).

Taxon	B-before	B-during	C-before	C-during	D-before	D-during	Total
Tardigrada			0.0017	0.0028			0.0008
Nematoda		0.0175	0.0044	0.0483	0.0035	0.0171	0.0176
Oligochaeta	0.0018	0.0559	1.1638	1.8332	0.0376	0.0625	0.5508
Acarina	0.0110	0.0594	0.0079	0.0853	0.0105	0.0369	0.0402
Crustacea							
Amphipoda		0.0017					0.0003
Ostracoda		0.0087	0.0017	0.0057		0.0085	0.0048
Cladocera*	0.0004	0.0017					0.0004
Copepoda calanoida							
*Acanthodiaptomus denticornis**		0.0052					0.0010
Copepoda cyclopoida							
*Cyclops abissorum tatricus**			0.0017	0.0455	0.0017	0.0256	0.0147
Diacyclops bisetosus			0.0009	0.0028		0.0028	0.0013
Diacyclops italianus			0.0017				0.0002
Diacyclops languidus			0.0009				0.0001
Eucyclops serrulatus			0.0026			0.0028	0.0009
Paracylcops imminutus				0.0028		0.0028	0.0011
Unidentified cyclopoida larval stages**			0.0009				0.0001
Copepoda harpacticoida							
Attheyella crassa		0.0017					0.0003
Bryocamptus (*Arcticocamptus*) *cuspidatus*	0.0044	0.0087	0.0017				0.0026
Bryocamptus (*Arcticocamptus*) *rhaeticus*	0.0127	0.0349					0.0087
Bryocamptus (*Echinicamptus*) *echinatus*	0.0026		0.0026				0.0007
Bryocamptus (*Rheocamptus*) *pygmaeus*	0.0013	0.0035					0.0008
Bryocamptus (*Rheocamptus*) *tatrensis*	0.0013	0.0035	0.0009				0.0010
Bryocamptus (*Rheocamptus*) *zschokkei*	0.0119	0.0280	0.0052	0.0028			0.0084
Maraenobiotus vejdovski	0.0004		0.0026				0.0004
Moraria alpina	0.0013	0.0017	0.0009				0.0006
Unidentified *Cryocamptus* larval stages**	0.0031						0.0004
Insecta							
Ephemeroptera Heptageniidae larvae		0.0297	0.0009	0.0227		0.0028	0.0112
Ephemeroptera Baetidae larvae	0.0145	0.3897	0.0149	0.2842	0.0114	0.2189	0.1840
Plecoptera larvae	0.0242	0.5906	0.0183	0.4178	0.0114	0.1222	0.2333
Aquatic Coleoptera larvae unidentified		0.0017		0.0171		0.0114	0.0060
Coleoptera Elminthidae adults			0.0009	0.0057		0.0028	0.0019
Coleoptera Hydraenidae adults		0.0017	0.0009	0.0085	0.0009		0.0023
Diptera Blephariceridae larvae		0.0035					0.0007
Diptera Ceratopogonidae larvae			0.0009			0.0028	0.0007
Diptera Chironomidae larvae and pupae	0.4446	3.1681	0.4875	4.0047	0.4255	3.8256	2.3807
Diptera Dixidae larvae	0.0009	0.0052	0.0009	0.0028		0.0114	0.0041
Diptera Limoniidae larvae	0.0018	0.0716	0.0017	0.0313		0.0057	0.0222
Diptera Psychodidae larvae and pupae	0.0022	0.0751	0.0096	0.3496	0.0052	0.1677	0.1208
Diptera Simuliidae larvae	0.0013	0.0542	0.0009	0.0654	0.0070	0.1307	0.0513
Trichoptera larvae	0.0044	0.1450	0.0096	0.1165	0.0035	0.0853	0.0717
Terrestrial taxa*	0.0171	0.5539	0.0507	0.9635	0.0952	0.5542	0.4361
Number of identified benthic taxa	18	24	27	20	10	19	
Total mean drift over all benthic taxa	1	5	2	7	1	5	
Ratio of "during" to "before"	9		4		9		

Densities calculated as mean value for all samples collected before (samples 1–4, 3 stations, 3 replicate each – total of 36 samples) and during (samples 5–10, 3 stations, 3 replicate each – total of 54 samples) the hydropeaking wave, and as total calculated as mean value over all 90 samples. *=Taxa removed from statistical analysis, i.e. planktonic Crustacea, and terrestrial taxa (Araneae, Miriapoda, Collembola, adult Diptera, Hemiptera Ephemeroptera, Thysanoptera, and riparian Coleoptera; Formicoidea, Hymenoptera, terrestrial Isopoda, larvae of Lepidoptera). **=Larval stages of Copepoda, which were not identified to the species level, and could not be attributed to any of the Copepoda taxa listed, and were not included in the calculation of the number of taxa.

reached with the arrival of the hydropeaking wave at station B (sample 5), and after 5 min from the arrival of the wave at stations C and D (sample 6; Fig. 6). After the peak in abundance, densities of drifting invertebrates decreased at all three stations, and 30′ after the beginning of the wave (sample 10) densities were again similar to those recorded before the wave at C and D, and remained slightly higher at B (Fig. 6); in fact, although the *R* values of the pairwise comparisons were not significant, they scored −0.15 when comparing samples 9 and 10 at station B, and 0.48 and 0.85, respectively, at C and D, indicating a higher similarity for station B for those samples (value closer to 0). Most larvae of Baetidae, Psychodidae, Trichoptera, Simuliidae, and Acarina (Fig. 5b, c, e, f, h) peaked at the onset of the hydropeaking wave; the *R* value was significantly different for each of these taxa between samples 4 (collected immediately before the peak) and 5 (arrival of the peak), and samples 4 and 6 (5 min after the beginning of the wave). Among this group of taxa, Baetidae decreased significantly in drift over time (*p* values indicated significant differences for the pairwise comparison of samples 5–6, 5–7, 5–8, 5–9, 5–10); Acarina and Simuliidae continued drifting during the wave (the same samples did not differ significantly), and so did Psychodidae and Trichoptera, which nonetheless were significantly reduced in drift after 30 min (differences between samples 5 and 10 were statistically significant). Most Chironomidae, Plecoptera, and terrestrial taxa peaked in drift after 5 min from the beginning of the wave (Fig. 5a, d, i; sample 6 differed significantly from the "before" samples for all taxa, and for most of the "during" samples for Chironomidae and terrestrial taxa); Plecoptera continued drifting (no significant differences between each pair of samples collected "during")

Table 2
Results of SIMPER analysis of drift data in the Noce Bianco Stream (Trentino, Italy): mean abundance of taxa that contributed to 90% of the total abundance at the two stations being compared, and mean dissimilarity between each pair of station for each of the taxa that reached a cumulative contribution of 90% to dissimilarity between stations. L: larvae; P: pupae.

Taxon	Mean abundance at station B	Mean abundance at station C	Mean abundance at station D	Mean Bray–Curtis Dissimilarity Index between stations B and C	Mean Bray–Curtis Dissimilarity Index between stations B and D	Mean Bray–Curtis Dissimilarity Index between stations C and D
Oligochaeta	0.034	1.565	0.053	21.03	2.12	20.73
Diptera Chironomidae L P	2.079	2.598	2.466	17.51	24.7	19.6
Plecoptera L	0.364	0.258	0.078	6.31	7.24	3.97
Ephemeroptera Baetidae L	0.24	0.176	0.136	4.32	5.29	3.44
Psychodidae L P	0.046	0.214	0.103	3.58	2.75	3.92
Trichoptera L	0.089	0.074	0.053	2.09	2.6	1.81
Acarina	0.04	0.054	0.026	1.41	1.36	
Diptera Simuliidae L	0.033	0.04	0.081	1.02	2.1	1.82

For sampling stations location, see Fig. 1.

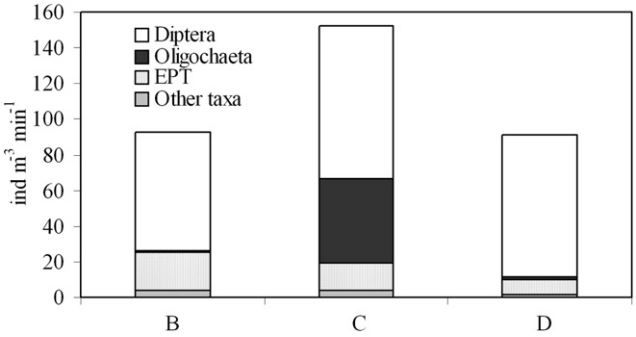

Fig. 2. Mean loss from bed of drifting aquatic invertebrates (ind m^{-3} min^{-1}) in each station on the Noce Bianco Stream, Trentino, Italy, calculated as mean value for all samples collected. For easier visual interpretation, taxa are pooled into four main groups: all Diptera larvae and pupae; Ephemeroptera, Plecoptera and Trichoptera (EPT); Oligochaeta; and all the remaining aquatic benthic taxa. For sampling stations location, see Fig. 1.

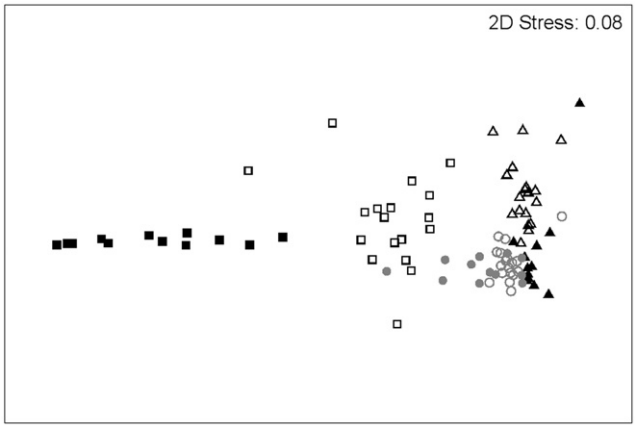

Fig. 3. Non-metric multidimensional scaling (NMDS) ordination of drift samples, based on Bray–Curtis Similarity Index. Triangles: station B; squares: station C; circles: station D. Solid symbols: samples collected before the hydropeaking wave; open symbols: samples collected during the wave. For sampling station locations, see Fig. 1.

whereas after 30 min Chironomidae and terrestrial taxa had significantly decreased in drift (significant differences between samples 5–8 and the last one). Oligochaeta and all benthic

Table 3
Results of ANOSIM analyses for drift data transformed in Log (x+1).

Analysis design	Station B		Station C		Station D	
	R	p	R	p	R	p
One-way, BEFORE-DURING	0.866	0.001	0.590	0.001	0.941	0.001
One-way, time	0.484	0.001	0.701	0.001	0.769	0.001

P: significance level. For sampling stations location, see Fig. 1.

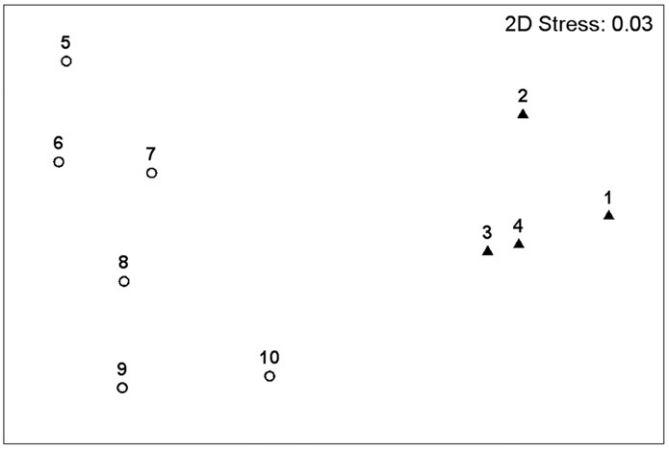

Fig. 4. Non-metric multidimensional scaling (NMDS) ordination of time samples calculated over all stations in the Noce Bianco Stream, Trentino, Italy, based on the R significance values of pairwise comparisons between pairs of time samples over all stations. White circles: time samples collected before the hydropeaking wave (samples 1–4) and black triangles: time samples collected during the hydropeaking wave (samples 5–10). For sampling station locations, see Fig. 1.

Copepoda and Nematoda (Fig. 5g, j, l) increased but did not follow a clear pattern (no significant differences were recorded between sample 4 and each of the 5–10 samples, nor for each pair of the "during" samples).

Discussion

The hydropeak was accompanied by an increase of conductivity and a decrease in temperature. Details of

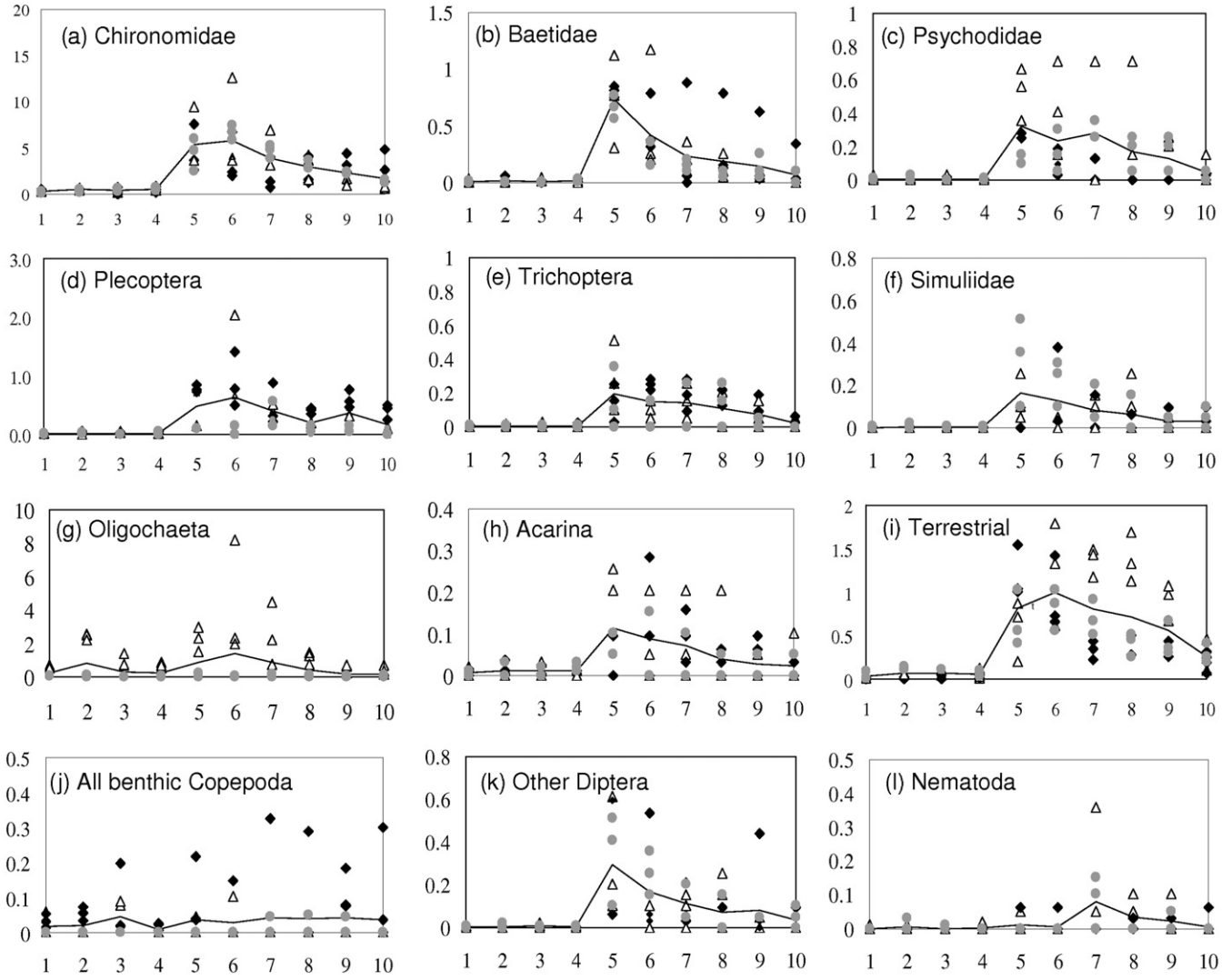

Fig. 5. Mean loss from bed of drifting aquatic invertebrates (ind m^{-3} min^{-1}) in each station for each time sample in the Noce Bianco Stream, Trentino, Italy. Taxa in figure are those that contributed most to the dissimilarities between all three stations (see Table 2). All terrestrial taxa, Nematoda, and all Copepoda are added because they represent the impact on riparian habitat, and on the benthic/hyporheic interface, respectively. Black rhombs: station B; white triangles: station C; grey circles: station D; continuous line: mean of all samples. For sampling station locations, see Fig. 1.

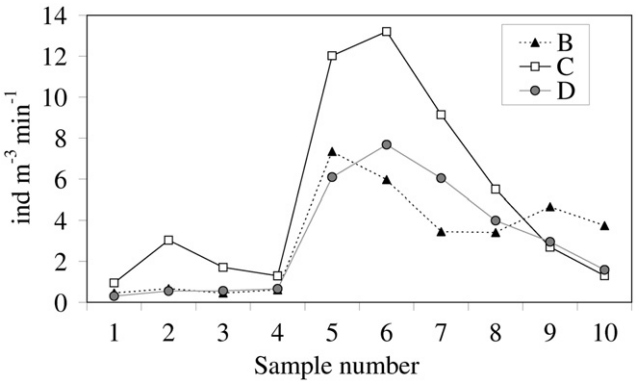

Fig. 6. Loss from bed of drifting aquatic invertebrates (ind m^{-3} min^{-1}) in each station for each drift sample in the Noce Bianco Stream, Trentino, Italy, calculated by averaging three replicates for each sample. For sampling station locations, see Fig. 1.

hydropower induced thermal alterations in the Noce River have been discussed elsewhere (Carolli et al., 2009) and, although their effects on the benthic community in inducing drift cannot be excluded, they were not investigated in this study. Mobilization of the gravel riverbed did not occur, largely due to armouring, a known consequence of repeated hydropeaking (e.g. Wong and Parker, 2006), and although POM, FPOM, and fine sediments were transported by the hydropeaking wave, the benthic communities responded to the increase in discharge with an increase in drift for a considerable distance downstream of the release point. Although drift has usually been investigated in association with physical disturbance of the substrate, Gibbins et al. (2007a, b) demonstrated that mass drift of invertebrates can be triggered by bed instability, and drift can also occur when sediment is being agitated rather than transported downstream.

The short time-scale and the reach spatial-scale used in this study allowed the assessment of the effects of a single

hydropeaking wave. These effects were explored through research questions which will be discussed separately below.

What are the effects on invertebrates of the arrival of the hydropeaking wave, and how far downstream do such effects propagate?

The increase in drift recorded as a response of the benthic communities to the hydropeaking wave was recorded from the water release point to the station 8 km downstream, though slightly attenuated with increasing distance (less taxa were drifting). Other studies on macroinvertebrates in hydropeaking impacted river reaches assessed effects at a shorter distance downstream from the release point; for instance, Céréghino et al. (2002, 2004) and Céréghino and Lavandier (1998a, 1998b) studied sites as far as 4.375 km downstream from the hydropower releases, and found a reduction in abundance of several benthic species starting from the stations at 30 m downstream from the outlet, with effects propagating to the downstream-most station (Céréghino et al., 2002, 2004), and reduced densities and biomasses of Plecoptera and Ephemeroptera at 700 m downstream from the plant (Céréghino and Lavandier, 1998a, b). In a study on experimental floods on stream benthos downstream from a large dam, Jakob et al. (2003) selected stations reaching 2.3 km downstream from the release point, and macroinvertebrates (in numbers and richness) were affected by the floods at all three stations, although responses varied for different taxa. We recorded differential responses for some taxa due to local effects; the higher number of drifting individuals found at the station 6 km downstream (station C) was mostly due to drifting Oligochaeta and Psychodidae, which were very abundant only at this station, probably as a consequence of local enrichment in FPOM from farms and households located near the stream in that area. In our study, the composition of drift was similar to that reported elsewhere, with juvenile instars of Ephemeroptera, Plecoptera, Trichoptera, and Chironomidae as dominant taxa (e.g. Brittain and Eikeland, 1988; Céréghino et al., 2002, Robinson et al., 2004a).

In the Noce Stream, hydropeaking primarily impacted the benthic invertebrate communities, but impacts on the riparian and terrestrial invertebrates were recorded as well. The impacts were represented by the direct removal of invertebrates through drift, which were washed out within 30 min; in fact, the rapid rise of water level associated with hydropeaking is known to strongly affect the terrestrial riparian communities (Perry and Perry, 1986; van Looy et al., 2006). Recent research by Paetzold et al. (2008) indicated that although riparian arthropods are highly mobile and can follow the moving shoreline in hydropeaking-impacted rivers, the combined effects of hydropeaking and channelization create unsuitable habitat conditions for all riparian arthropods, as a result of the associated increases in inundation frequency and loss of interstitial habitats through increased substrate embeddedness.

Can a temporal timeframe be detected in drift for different taxa, even if the discharge, once artificially increased, remains constant?

Drift increased with increasing discharge and macroinvertebrates were removed from the sediment in a short time interval, though the discharge increased from 1 to 7 $m^3 s^{-1}$ in about 10 min and remained stable for the remainder of the experimental release. Invertebrates responded to the hydropeaking wave quickly; drift peaks were recorded during the rising phase, 5–10 min from the beginning of the flow increase. Most drift occurred within the first 15 min of high discharge, with drift abundance and composition returning to near base-flow levels for most of the benthic taxa after 25 min. A similar temporal pattern was recorded by several authors in experimental flow manipulations in artificial channels (e.g. Imbert and Perry 2000; Mochizuki et al., 2006) and in natural rivers (Robinson et al., 2004a).

Habitat preferences and/or behavioral adaptations can affect drift abundance more than changes in magnitude (discharge and duration of peak flows) of high flows (Holomuzki and Biggs, 2000; Mochizuki et al., 2006). Jakob et al. (2003) reported how taxa ill-adapted to high flows or increases in velocity (particularly Trichoptera) were more susceptible to flood disturbance regardless of longitudinal position downstream of the dam. In this case study, drift responses by different species occurred with different timeframes, and most taxa with no morphological or behavioral adaptations to high flow velocity had a passive drifting response and in fact some taxa were depleted from benthos very quickly (Baetidae, which decrease in abundance in drift after 5 min from the beginning of the wave) or slightly more slowly (Psychodidae, Trichoptera, and Chironomidae).

Most of the taxa that increased in the drift at the arrival of the wave were associated with algae and organic debris, which are washed off by the increases in discharge (Irvine and Henriques, 1984; Irvine 1985); these taxa are shredders, scrapers, detritivores or filter feeders, or prey on the former (larvae of Psychodidae, Baetidae, Simuliidae; Acarina and very early instars of Trichoptera, Plecoptera, and Heptageniidae). Other taxa initially reached the maximum density in drift with a delay of 5–10 min (mainly larvae of Chironomidae and Plecoptera), or continued drifting during the entire experimental wave (Plecoptera, Acarina, and Simuliidae) because they have morphological (hydrodynamic body shapes, hooks, and other structures enabling them to cling to the substrate) or behavioral (hiding underneath rocks, moving to areas of low velocity, etc.) adaptations (Hart and Finelli, 1999; Holomuzki and Biggs, 2000; Jakob et al., 2003) to resist the shear stress and were washed out with a delay (Chironomidae and Plecoptera) and in some cases with a low rate (Acarina, Simuliidae). Chironomidae were the dominant taxa in drift, as commonly reported in literature (e.g. Imbert and Perry, 2000; Robinson et al., 2004b). They are usually reported to respond immediately to increase in discharge (Robinson et al., 2004a; Jakob et al., 2003), whereas in experimental stepwise increases in flow (Imbert and Perry, 2000), chironomids reached significantly high values in drift after the second or third increase in discharge (i.e. 60–90′ from the beginning of the discharge increase) because they inhabited margins and slow flowing sections. Chironomidae in our samples belonged mostly to the cold-stenothermal, carnivorous subfamily Diamesinae, associated to fast flowing waters. Unlike detritivorous chironomid subfamilies associated with fine sediments, Diamesinae were not washed away when the hydropeaking wave initially removed the FPOM, but only when the velocity was high enough to dislodge them from coarser substrates. Some taxa were not (Harpacticoida) or only slightly (Nematoda) affected from the disturbance of the hydropeaking wave because they were associated with the hyporheic habitat, which is sheltered from the bottom shear stress. For instance, several taxa of Harpacticoida and Cyclopoida, which are often present in the hyporheic (Stoch, 2006), and in the hyporheic of this same reach as well (Bruno et al., 2009), were more abundant in drift before the hydropeaking wave than during the wave, suggesting that they find a refuge from the increase in shear stress by dwelling deeper into the sediment.

Each hydropeaking wave causes a considerable part of the benthic communities to drift downstream, and recolonization from upstream (by drift), downstream (adults migrations and egg deposition), and from the sediment (vertical migration from the shallow hyporheic zone) must therefore occur continuously (e.g. Williams, 1977; Dole-Olivier et al., 1997). In Alpine rivers, studies on experimental floods showed that benthic communities reach or even exceed pre-flood densities after 20 and 35 days (Robinson et al., 2004b), and drifting organisms are more than sufficient to recolonize benthic habitats in natural flow conditions (Smith and

Brown, 2006). Recolonization from the shallow hyporheic can represent an important source for benthic communities, which can use the hyporheic habitat as a refuge to avoid environmental stress (Dole-Olivier et al., 1997), and thus to avoid catastrophic drift during hydropower production operations, and the hyporheic can function as a reservoir able to colonize depleted benthic habitats (Townsend and Hildrew, 1994). However, in the same reach of the Noce Stream investigated here, hyporheic invertebrates diversity and abundance were reduced in the hydropeaking-impacted sites (Bruno et al., 2009), thus decreasing the role of this zone as a source of recolonization to the benthic communities.

Hydropeaking events with the magnitude of the experimental release occur daily in the Adige watershed, and normally last about 12 h (Zolezzi et al., 2009); in the Noce Stream such daily hydropeaking waves cause a considerable part of the benthic communities to drift downstream, as already recorded in several other studies (e.g. Imbert and Perry, 2000). Larger-sized individuals are more easily removed, while smaller organisms or very early instars may survive by taking refuge in the sediment. In time, these changes might modify the structure and composition of downstream benthic communities (Céréghino et al., 2002); in fact, once a species is lost from a stream it cannot be assumed to recolonize spontaneously (Hughes, 2007). As a consequence, in the investigated stream, the repeated high-flow events of similar magnitude cause considerable losses from benthic populations to drift and longitudinal differences in drift composition can indicate long-term cumulative effects of years of hydropeaking.

This paper contributes to a better understanding of the responses of benthic invertebrates to hydropeaking-induced disturbance in Alpine streams. Possible stream restoration measures should include impacts induced by hydropeaking as a necessary step towards fully successful restoration projects. Where feasible, amelioration of hydropeaking should be a primary goal while planning operational and structural changes in hydropower plants.

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